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Intralake heterogeneity of thermal responses to climate change: a study of large northern hemisphere lakes

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RESEARCH ARTICLE
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Key Points:
- Large lakes experience considerable intralake heterogeneity of thermal responses to climate change
- The deep areas of large lakes tend to display higher rates of summer temperature warming
- Single-point lake temperature trends suppress important aspects of lake responses to climate change

Supporting Information:
- Supporting Information S1

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Intralake Heterogeneity of Thermal Responses to Climate Change: A Study of Large Northern Hemisphere Lakes

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Abstract Lake surface water temperature (LSWT) measurements from various sources illustrate that lakes are warming in response to climate change. Most previous studies of geographical distributions of lake warming have tended to utilize data with limited spatial resolution of LSWTs, including single-point time series. Spatially resolved LSWT time series are now available from satellite observations, and some studies have investigated previously the intralake warming patterns in specific lakes (e.g., North American Great Lakes). However, across-lake comparisons of intralake warming differences have not yet been investigated at a large, across-continental scale, thus limiting our understanding of how intralake warming patterns differ more broadly. In this study, we analyze up to 20 years of satellite data from 19 lakes situated across the Northern Hemisphere, to investigate how LSWT changes vary across different lake surfaces. We find considerable intralake variability in warming trends across many lakes. The deepest areas of large lakes are characterized by a later onset of thermal stratification, a shorter stratified warming season and exhibit longer correlation timescales of LSWT anomalies. We show that deep areas of large lakes across the Northern Hemisphere as a result tend to display higher rates of warming of summer LSWT, arising from a greater temporal persistence in deep areas of the temperature anomalies associated with an earlier onset of thermal stratification. Utilization of single-point LSWT trends to represent changes in large lakes therefore suppresses important aspects of lake responses to climate change, whereas spatially resolved LSWT measurements can be exploited to provide more comprehensive understanding.

1. Introduction

Lakes act as sentinels of climate change, where any changes in the surrounding catchment or overlying atmosphere due to climatic variations will reflect on the ecosystem (Adrian et al., 2009; Williamson et al., 2009). A direct impact of climate on lakes is climate-driven modulation of lake surface water temperature (LSWT), with potential consequences for a broad range of physical and ecological factors (De Stasio et al., 1996). Rising LSWTs can influence metabolic processes (Kraemer et al., 2017), enhance greenhouse gas emissions (Yvon-Durocher et al., 2014) and modify the key processes of vertical mixing and stratification leading to an increased occurrence of cyanobacterial blooms (Jöhnk et al., 2008), deepwater hypoxia (Jankowski et al., 2006; North et al., 2014) and changes in lake productivity (O'Beirne et al., 2017; O'Reilly et al., 2003). A detailed understanding of LSWT warming, and the factors that control it, is therefore essential for climate change impact studies.

LSWTs have been measured around the world for many years (Austin & Colman, 2008; Dobiesz & Lester, 2009; Kainz et al., 2017; Magee et al., 2016; Pareeth et al., 2017; Roberts et al., 2017; Woolway, Dokulil, et al., 2017), and recent efforts have collated some of these measurements to investigate global patterns of LSWT trends (Sharma et al., 2015). A global synthesis of satellite-derived and in situ LSWT observations demonstrated that lakes have been warming in recent decades (O'Reilly et al., 2015). For high-latitude large, deep lakes, the combination of milder winter conditions, increases in solar radiation (Schmid & Köster, 2016; Wild, 2012), and rising surface air temperatures (SATs) in spring have resulted in a stronger and earlier onset of stratification, and consequently an amplification of summer LSWTs (Austin & Colman, 2007; Piccolroaz et al., 2015; Zhong et al., 2016). Stratification onset can have a considerable influence on LSWT as a result of the nonlinear thermal response that occurs when LSWT crosses the 4°C threshold and the layer of water that interacts directly with the atmosphere begins to transition from the full lake depth to a much shallower upper mixed layer. As LSWTs increase more rapidly when the volume of water that participates directly in air-water surface heat exchange is smaller, an earlier stratification onset can result in an increase in the time during which the shallow upper mixed layer is present and, in turn, result in a stronger trend in LSWT than would be expected from changes in SAT alone (Austin & Colman, 2007; O'Reilly et al., 2015). However, the role of stratification onset on summer LSWT can vary among lakes, with temperature anomalies associated with stratification onset persisting only for a sufficient time to influence summer LSWT when the number of days between stratification onset and midsummer is short (e.g., high-latitude and high-altitude lakes) and thermal inertia is large (e.g., deep lakes) (Woolway & Merchant, 2017). In turn, cold and deep lakes often display an amplified response to SAT variability as a result of a greater persistence of temperature anomalies induced by an earlier onset of stratification (Woolway & Merchant, 2017).

While there is sufficient evidence to demonstrate that lakes are warming globally (O'Reilly et al., 2015), many long-term LSWT analyses have been limited in spatial resolution and have either investigated lake-wide average temperatures (Woolway & Merchant, 2017) or measurements from one (or a few) location(s) per lake (Austin & Colman, 2007; O'Reilly et al., 2015; Schneider & Hook, 2010). Analyses of spatially resolved LSWTs provide evidence of intralake warming patterns, with warming rates often differing at the subbasin scale (Kraemer et al., 2015; Mason et al., 2016; Petchprayoon, 2015; Zhong et al., 2016). The Laurentian Great Lakes, for example, show intralake patterns in warming trends, often associated with shortening winter ice cover as well as other geophysical factors, such as bathymetry (Mason et al., 2016). In particular, higher summer warming rates have been reported over the deepest parts of the Laurentian Great Lakes (Mason et al., 2016; Petchprayoon, 2015; Zhong et al., 2016), as a result of more rapid changes in stratification onset date in the deepest regions (Petchprayoon, 2015). Such analyses of spatially resolved LSWTs have been pivotal in improving our understanding of the heterogeneity of intralake thermal responses to climate change and the underlying mechanisms. These studies have focused on a small number of lakes within a specific region, making it worthwhile to quantify how intralake warming patterns differ more broadly. In addition, while previous analyses in the Laurentian Great Lakes have identified heterogeneous intralake summer warming as a result of greater changes in stratification onset in the deepest regions (Petchprayoon, 2015), other studies have shown that summer LSWTs in some lakes are less sensitive to early-season thermal anomalies (Woolway & Merchant, 2017). While there is a good appreciation of heterogeneous intralake warming differences in the Laurentian Great Lakes, the extent to which such spatial patterns are evident in other large lakes globally requires further investigation. In particular, no study has previously also looked at patterns within large lakes in Europe, nor in large, but very shallow lakes.

In this paper, we analyze up to 20 years of spatially resolved satellite-derived LSWT observations from some of the world's largest lakes situated across the Northern Hemisphere and investigate if the deepest regions of large lakes are more sensitive than shallower regions to early-season thermal anomalies and thus display an amplified intralake thermal response to climate change. It is expected that a number of other factors can influence spatially resolved LSWT trends (Mason et al., 2016). Nonetheless, in this study, we assess how spatial variations in early-season lake conditions can influence summer LSWTs, and the degree to which such spatial variations can be explained by lake morphometry.

2. Methods

2.1. Lake Surface Water Temperature

In this study, we utilize LSWTs from the Along Track Scanning Radiometer (ATSR) Reprocessing for Climate: LSWT and Ice Cover (ARC-Lake) data set (MacCallum & Merchant, 2012), available at http://www.laketemp.net. LSWT observations are derived from the ATSR series, which consists of ATSR-1 (1991–1996), ATSR-2 (1995–2002), and Advanced(A)ATSR (2002–2011), and retrieved at a spatial resolution of ~1 km at nadir and then averaged to 0.05° cells, where each 0.05° cell has an uncertainty in the order of 0.4°C (relative standard deviation). The ARC-Lake data set includes day and nighttime retrievals. The average temporal resolution of LSWT retrievals is <1 week (Layden et al., 2015). Spatially complete daily-resolution LSWTs are formed by reconstruction using empirical orthogonal functions (Alvera-Azcárate et al., 2005) of the whole-lake LSWT field from the intermittent and partial data coverage available from the satellite observations. LSWT observations in ARC-Lake are restricted to the world's largest lakes, principally those with surface area > 500 km^2, but include some lakes whose surface area is approximately 100 km^2.

In ARC-Lake, a target lake is identified on the basis of the geographical coordinates of a pixel in the ATSR imagery. A hierarchical, temporally fixed, land/water mask was developed specifically to define lake boundaries used in the ARC-Lake project by reconciling the global lakes and wetlands database polygon area (Lehner &

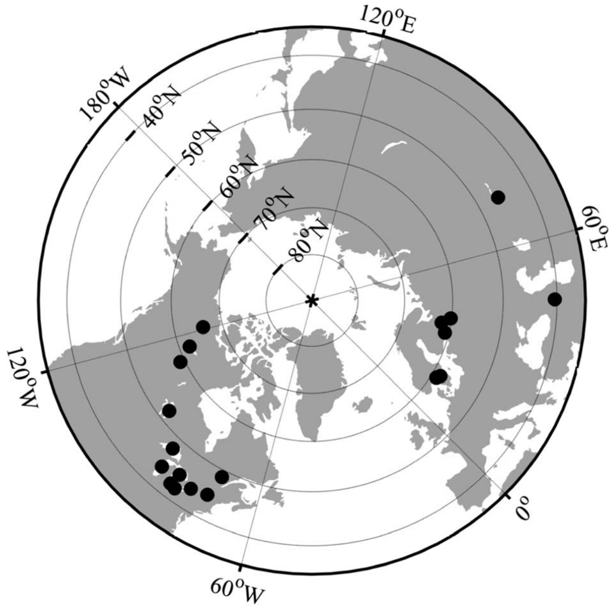

Figure 1. Location of each lake in which spatially resolved lake surface water temperature and bathymetric information were available and used in this study.

Döll, 2004) and the Naval Oceanographic Office data. The lake identification algorithm determines, on the basis of the latitude and longitude of a pixel in the ATSR level 1b imagery and this mask, whether that pixel is over a target lake. As this mask is temporally fixed, lakes with variable surface area (>25%) were excluded to avoid the issue of LSWT retrievals being spuriously obtained over land when the lakes recede.

Valid LSWTs are estimated only for pixels that are effectively free from cloud, where an algorithm based on Bayes' theorem (Merchant et al., 2005) was used for assigning a clear-sky probability. The effectiveness of the lake product retrieval algorithms is assessed using two methods of data validation: analysis of the performance for case study images at full ATSR resolution and quantitative point comparisons with in situ observations. A match-up data set from in situ temperature data consisting of 52 observation locations covering 18 lakes was constructed (MacCallum & Merchant, 2012). The mean differences ranged between the instruments from −0.34 to −0.09°C (day) and −0.18 to +0.06°C (night) (Layden et al., 2015). In this investigation we use daily averaged LSWTs, calculated as the average of the day and nighttime retrievals.

The length of the time series varies across the lakes monitored within the ARC-Lake project, depending on instrument coverage. Only lakes with observations from all three ATSR instruments are used in this study. In addition, as we are interested in the influence of early-season thermal anomalies on summer LSWTs, we select only lakes in which their surface temperatures cross from <4°C to >4°C during their climatological annual cycle, where 4°C is used as a threshold for stratification onset (Austin & Colman, 2007; Austin & Colman, 2008; Boehrer & Schultze, 2008; Moukomla & Blanken, 2016). Thus, we exclude permanently stratified lakes in this investigation. Also, as we are interested in the influence of depth on intralake warming, we also only include lakes for which bathymetry data were available from the Global Lake Database (v2) (Choulga et al., 2014). Within the above restrictions, 19 lakes could be investigated in this study (Figure 1). These lakes vary in their geographic and morphological characteristics. They range in altitude between 11 m above sea level to 1,876 m above sea level, in latitude between 40.39°N and 65.91°N, in surface area between 1,084 km^2 and 81,935 km^2, and in maximum depth between 6 m and 614 m (Table 1). In this investigation, in-line with previous LSWT studies (O'Reilly et al., 2015; Schneider & Hook, 2010), we calculate warming rates for the period July–September, which we define hereafter as "summer."

Table 1
General Characteristics of the Lakes Investigated in This Study

Lake name	Latitude (°N)	Longitude (°E)	Altitude (m)	Area (km^2)	Max. depth (m)
Superior	47.72	−88.23	184	81,935.7	407
Huron	44.78	−82.21	176	59,756.5	229
Michigan	43.86	−87.09	176	57,399.4	282
Great Bear	65.91	−121.3	157	30,530.1	413
Great Slave	62.09	−114.37	158	27,816.3	614
Erie	42.25	−81.16	174	25,691.0	64
Winnipeg	52.12	−97.25	217	23,809.3	28
Ontario	43.85	−77.77	75	19,328.9	245
Ladoga	60.84	31.39	11	17,539.1	230
Balkhash	45.91	73.95	329	17,458.8	26
Onega	61.9	35.35	56	9,608.1	120
Athabasca	59.1	−109.96	212	7,781.6	124
Vänern	58.88	13.22	45	5,550.5	98
Vättern	58.33	14.57	91	1,847.2	128
Sevan	40.39	45.29	1876	1,249.9	83
Saint Clair	42.5	−82.73	174	1,155.8	6
Saint Jean	48.66	−72.02	97	1,106.2	63.1
Beloye	60.18	37.64	122	1,095.4	20
Champlain	44.45	−73.27	35	1,084.1	122

Note. Shown are the names of each lake, their latitude, longitude, altitude, surface area, and maximum depth.

2.2. Statistical Methods

We analyzed long-term trends in summer LSWTs using ordinary least squares linear regression models, similar to Mason et al. (2016). Trends are estimated as the slope of a linear trend model, and correlations are assessed using the Pearson correlation coefficient. The 5% to 95% confidence interval for estimated values are also quoted: for example, a trend may be quoted as 0.10 (0.08; 0.13) °C yr^{-1}. This indicates that the best estimate slope is 0.10°C yr^{-1}, with 90% statistical confidence that the true value lies between 0.08 and 0.13°C yr^{-1}. All calculations were performed in R (R Development Core Team, 2014).

2.3. Comparison of Shallow and Deep Lake Surface Water Temperatures

For certain analyses comparing warming rates and lake surface temperature dynamics of the shallowest and deepest regions of each studied lake, we calculate separate time series of LSWT observations averaged across the shallowest 10% and deepest 10% of each lake. To ensure that the 10% threshold did not materially affect our analysis, we also repeated all calculations using 5%/95% and 20%/80% threshold for defining shallow/deep regions. These variants gave minimal differences in the results and for clarity are not shown. We also, in certain analyses, calculate average LSWT observations for different lake depth bins, ranging from 5% to 100% of the maximum lake depth, in 5% intervals, averaging all lake pixels that fall in each depth bin to generate 19 depth-stratified lake-mean time series for a given lake. We ignore the 0–5% lake depth bin to avoid the potential issue of contaminated pixels (i.e., inclusion of some land).

2.4. Correlation of Lake Surface Temperature Anomalies

We calculate the timescale on which anomalies in stratification onset correlate significantly with LSWT anomalies and thus determine how long stratification onset can influence LSWT, as follows (Woolway & Merchant, 2017). For a given lake pixel (0.05°) or lake-mean time series (see above), we calculate the interannual variability in stratification onset and the interannual variability in LSWT anomalies from each day thereafter up to the climatological day of year (DOY) in which maximum LSWT occurred. The difference between stratification onset and the DOY of maximum LSWT is hereafter referred to as the stratified period of warming. We then calculate the covariance (r^2) between the interannual variability in stratification onset and LSWT anomalies for each subsequent day. Thus, we evaluate how LSWTs are influenced by the preceding stratification onset and how this association varies temporally and spatially within a lake. We also calculate the length of time during which the anomalies in stratification onset and LSWT are correlated significantly. This metric is used to represent the timescale over which variations in stratification onset can be expected to have a significant influence on LSWT anomalies. To demonstrate the combined influence of the correlation timescales of lake thermal anomalies and the duration of the stratified period of warming on LSWT, we calculate the ratio of these two metrics. We would expect summer LSWTs to be influenced by stratification onset when this ratio is $\leq$1, that is, when the duration of the stratified period of warming is less than or comparable to the persistence in early-season thermal anomalies.

3. Results

An intralake depth dependence exists for the climatological stratification onset across each lake investigated in this study. Figure 2 illustrates this for the case of Lake Huron. (In this paper, we show example figures for several different lakes, each illustrating a particular point in the analysis, and then include a comparison of the most relevant metrics between the shallowest and deepest regions of all lakes in Figure 5. We also show the intralake patterns for each lake in the supporting information.) Across all study lakes, we calculate that stratification onset occurs 30 days later in the deepest regions compared to the shallowest regions, on average. The deepest regions of the lakes studied also experience a shorter stratified period of warming (e.g., Figure 2; see Figure 5 for summary across all lakes). Specifically, across all lakes, we find that the stratified period of warming is 26 days shorter in the deepest compared to the shallowest regions of lakes, on average. The time of maximum LSWT does not vary considerably (difference of 4 days, on average) across the surface of all study lakes (e.g., Figure 2; summary in Figure 5), although it varies substantially among lakes. Thus, the stratified period of warming length varies within lakes principally as a result of the depth dependence in stratification onset (Figures S1–S19).

As a result of the autocorrelation in LSWT (i.e., temperatures closer together are often more correlated), a shorter stratified period of warming in the deepest regions of lakes makes it more likely that thermal anomalies associated with stratification onset variability will have a greater influence on the LSWT attained during summer. To demonstrate the significance on summer LSWT of stratification onset and, in particular, the length of the stratified period of warming, we calculate the correlation between the anomaly in stratification onset and later anomalies in LSWT (see section 2). We calculate a decrease in the correlation between these anomalies with time across the lake surface, which illustrates a decreasing influence of stratification onset on LSWT as time progresses (Figure 3a). We also find a noticeable influence of lake depth; the decorrelation of lake thermal anomalies is faster in the shallower regions (Figure 3a). Specifically, our results show that the length of time in which LSWT anomalies are correlated significantly varies within a lake, with LSWTs in the deepest regions being influenced by early-warming-season thermal anomalies for longer. To demonstrate the combined influence of the length of the stratified period of warming (which is shorter in deeper regions) and the correlation timescales of lake thermal anomalies (which is longer in deeper regions) on LSWT, we

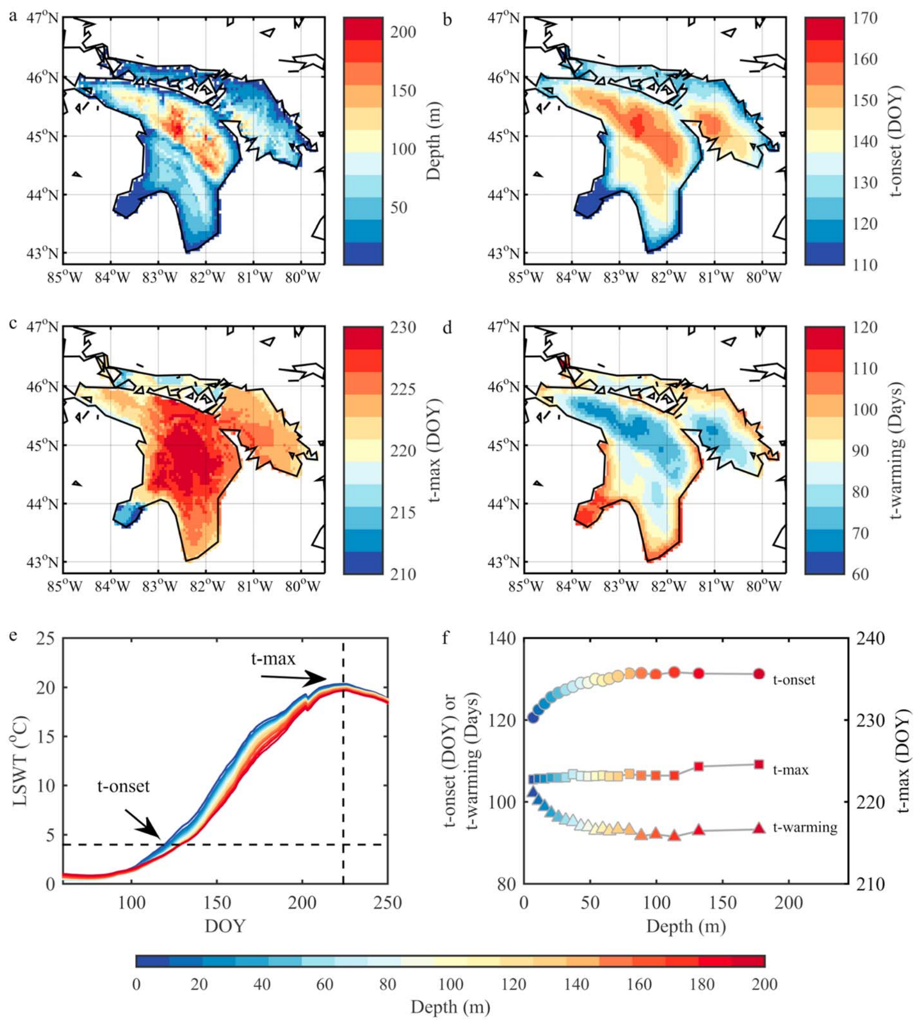

Figure 2. Examples from Lake Huron, North America, of (a) depth; (b) the climatological average stratification onset (t-onset); (c) the climatological average day of year (DOY) in which maximum lake surface water temperature (LSWT) occurred (t-max); (d) the climatological average length of the stratified warming period (t-warming), defined as the time difference (in days) between t-onset and t-max; (e) climatological (shown up to DOY 250) lake-mean LSWTs averaged across different lake depth bins (defined as a percentage of maximum lake depth at 5% depth intervals; see section 2), as shown in the colorbar; and (f) comparison of t-onset (circle), t-max (square) and t-warming (triangle) for LSWT observations averaged across different lake depth bins (similar to Figure 2e). Note different scale of *y* axis in Figure 2f.

calculate the ratio of the length of the stratified period of warming to the time during which LSWT anomalies are correlated significantly. We calculate that the ratio of these metrics is ≤ 1, which illustrates regions in which summer LSWT is influenced most by stratification onset variability, in the deepest regions and increases to >1 in the shallowest regions (Figure 3). In this sample of lakes, therefore, the length of the stratified period of warming is often shorter than or comparable to the persistence of early-season LSWT anomalies in the deepest region, but this is not the case in the shallowest regions.

This leads us to expect that the influence on summer LSWT of thermal anomalies associated with stratification onset will vary within lakes with depth. To explore this, we quantify the statistical relationship between stratification onset and summer LSWT variability and the influence of depth (which is influential indirectly via depth's association with the length of warming and the persistence of early-season thermal anomalies established above). We calculate the proportion of variance (r^2) shared between the interannual variability in stratification onset and that of the summer LSWT for each 0.05° lake pixel (e.g., Figure 4 showing the results for Lake Superior). We find that this covariance is higher in the deepest compared to the shallowest areas of lakes. Thus, the influence on summer LSWT of the anomaly in stratification onset varies systematically across a lake and is markedly greater in deeper regions. Higher correlation for the deepest areas is evident in all

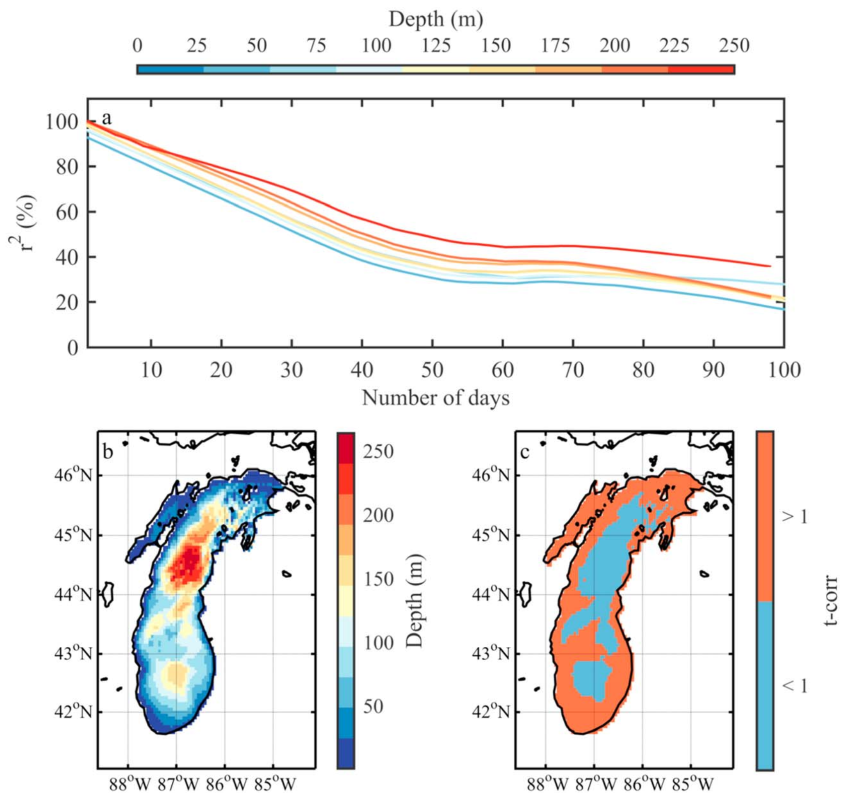

Figure 3. The covariance (r^2, %) between the interannual variability in stratification onset and lake surface water temperature (LSWT) anomalies for each subsequent day. Shown, for Lake Michigan, North America, are (a) the correlation timescales for lake-mean LSWT anomalies averaged across different lake depth bins (defined as a percentage of maximum lake depth at 5% depth intervals; see section 2), and spatially resolved (b) depth, and (c) the ratio of t-warming (length of the stratified warming period) to the time during which early-season LSWT anomalies are correlated significantly (t-corr).

study sites (Figure 5), and this is consistent with an interpretation of thermal anomalies persisting longer in the deepest regions of large lakes that have a shorter length of the stratified warming period. In contrast, in regions where the stratified warming period is long relative to the persistence of early-season thermal anomalies, summer LSWTs are influenced less by stratification onset. This generally occurs in the shallowest regions as the day-to-day chaotic variability of the weather erodes thermal anomalies more quickly.

Analyses of spatially resolved summer LSWTs demonstrate considerable spatial heterogeneity in warming rates (e.g., Figure 6 for Lake Huron), consistent with our expectations from the aforementioned analysis. In particular, we calculate that summer LSWTs in the deepest regions of lakes can increase at a rate almost twice that of the shallowest regions (e.g., Figure 6a). Among all lakes, we identify a positive linear trend in the deepest regions of all but one (Great Bear Lake) of the 19 study sites (Figure 7a). Overall, we find that the warming rates in the shallowest and deepest regions of lakes differ considerably (Figure 7). There exists a clear tendency for the deepest areas of inland water (combining the data across all the study lakes) to have more positive trends in summer LSWT (Figure 7b), with this contrast becoming most marked at depths deeper than about 100 m, which tend to have warmed with a trend 3 times faster than areas less than 30 m deep.

4. Discussion

Our analysis suggests that the intralake depth dependence of summer LSWT trends across the Northern Hemisphere arises as a result of a combination of two factors: first, that the deepest areas of large lakes have a climatologically shorter stratified warming season, due to a later climatological stratification onset; and second, that the deepest areas display a greater persistence of lake temperature anomalies. It has long been recognized that winter/spring LSWT anomalies associated with an earlier stratification onset are associated with relatively rapid summer LSWT warming (Austin & Colman, 2007). Our study shows that the two

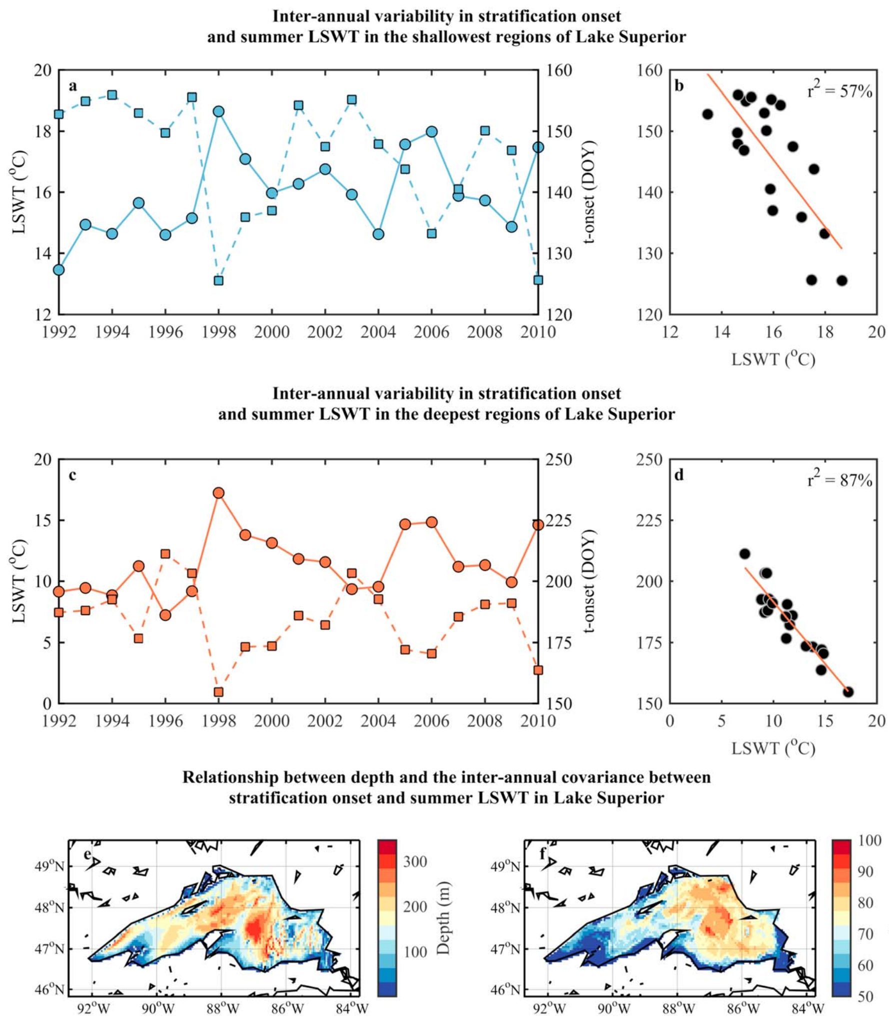

Figure 4. Examples from Lake Superior, North America, of the covariance (r^2) shared between the interannual variability in summer (July to September) lake surface water temperature (LSWT, solid line) and stratification onset (t-onset, dashed line). Shown are comparisons for the shallowest (a, b) and deepest (c, d) regions of the lake (defined as the shallowest and deepest 10% of lake depths; see section 2). Linear regressions of the statistically significant ($p < 0.05$) relationships are shown. A comparison of depth (e) and the calculated covariance (f) in each 0.05° pixel is shown. DOY = day of year.

identified factors together mean that such anomalies have a greater influence on summer LSWT in the deeper areas of large lakes than in shallower areas thus explaining, in part, the mechanism of intralake warming noted previously in a few large North American lakes (Mason et al., 2016; Petchprayoon, 2015; Zhong et al., 2016). Furthermore, our study demonstrates that the intralake warming variations noted in previous studies are also valid across many lakes situated across the Northern Hemisphere, including those that are relatively shallow in comparison.

The first factor we identify that promotes relatively rapid summer LSWT warming is the later climatological stratification onset in the deepest regions of large lakes. This has been shown previously for some of the Laurentian Great Lakes (Austin & Colman, 2007), but our study is the first to show this relationship across many lakes situated throughout the Northern Hemisphere. The depth dependence of stratification onset (Malm & Jönsson, 1993; McCormick, 1990; Ullman et al., 1998) is a result of a period of deep convective mixing that typically occurs in the deepest regions of lakes prior to surface waters reaching 4°C in spring. Specifically, in many large north temperate lakes, winter LSWTs are typically below the temperature of maximum density (e.g., during ice cover), resulting in an inversely stratified water column and the formation of a colder, less dense upper mixed layer above denser, warmer bottom waters (Titze & Austin, 2014). Springtime heating warms near-surface waters, increasing water density and resulting in convective mixing through a deep volume of water with large thermal inertia. In comparison, springtime heating can bring a more rapid rise

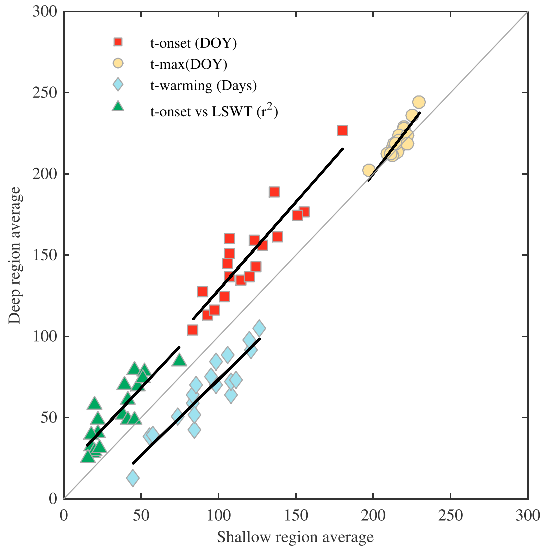

Figure 5. Comparison among the shallowest and deepest regions of each lake (defined as the shallowest and deepest 10% of lake depths; see section 2) of the climatological stratification onset (t-onset, red), the climatological average day of year (DOY) in which maximum lake surface water temperature (LSWT) occurred (t-max, yellow), the climatological average length of the stratified warming period (t-warming, blue), defined as the time difference between t-onset and t-max, and the covariance (r^2; %) shared between the interannual variability in summer (July to September) LSWT and the interannual variability in t-onset (green). Linear regressions of the statistically significant ($p < 0.05$) relationships are shown. Gray line shows the 1:1 relationship.

in LSWT in shallow regions, that is, in areas whose depth is less than the depth of the deepwater convective mixing which therefore have a smaller thermal inertia. Note that this simplified "one-dimensional" explanation in terms of thermal inertia is in reality significantly modified by effects of circulation.

The second factor we identify is the depth dependence in the correlation timescales of lake thermal anomalies, whereby lake surface temperatures in the deepest regions of lakes are correlated for longer. This is a result of the spatial variations in the depth of the upper mixed layer in summer. Where the depth of the upper mixed layer is deep (and thus of higher volume), surface waters will be less sensitive to day-to-day weather variability. The LSWT for deep areas thus tends to display a greater persistence of thermal anomalies associated with anomalies in stratification onset. The depth of the upper mixed layer in deep regions of a lake can be many tens of meters, which can be deeper than the shallows of the same lake. In shallow areas day-to-day changes in weather can be expected to erode established thermal anomalies more quickly. Our study is the first to demonstrate the intralake heterogeneity in the temporal persistence of temperature anomalies.

Given the two identified factors (stratification onset and persistence), we can hypothesize about differences in the behavior of summer LSWTs between dimictic, monomictic and polymictic lakes. Dimictic lakes mix fully twice per year and inversely stratify in winter and positively stratify in summer. They are subject (at least in deep regions) to both identified factors, and so we expect dimictic lakes typically to display spatial contrasts in summer LSWT variability. Monomictic lakes are those that mix fully once per year (they do not usually inversely stratify in winter). For this reason, we expect them to be subject to the persistence factor but not to have

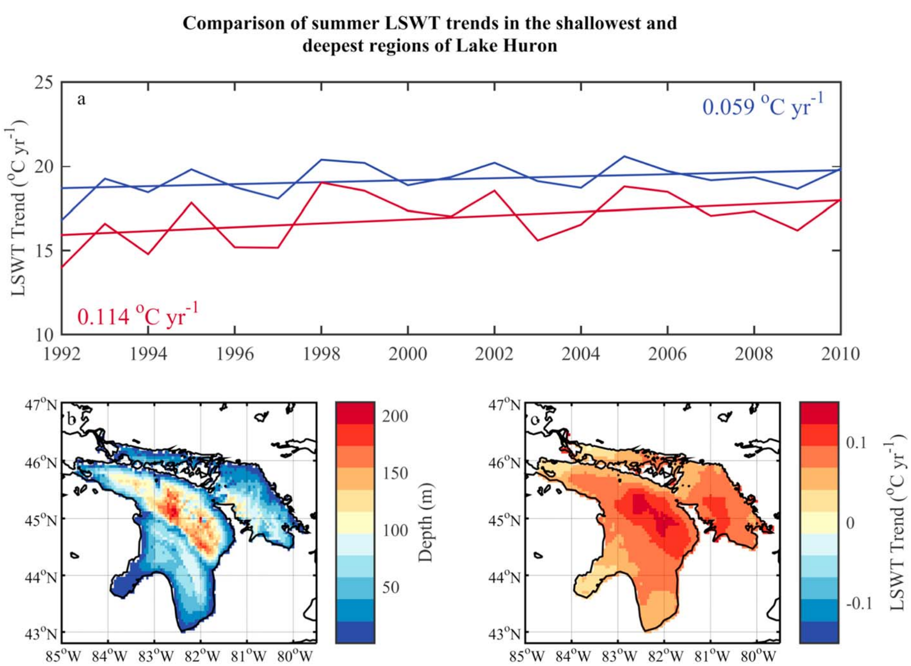

Figure 6. Example from Lake Huron, North America, comparing (a) summer lake surface water temperature (LSWT) warming rates between the shallowest (blue) and deepest (red) regions (defined as the shallowest and deepest 10% of lake depths; see section 2), and spatially resolved, (b) depth and (c) satellite-derived summer (July to September) LSWT trends.

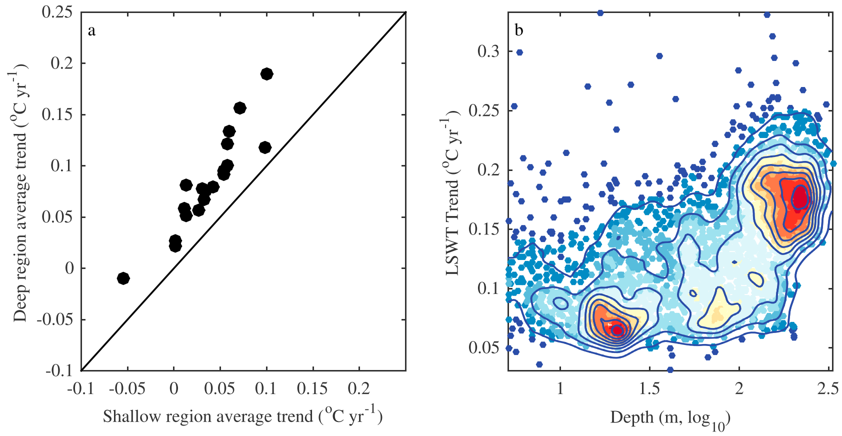

Figure 7. (a) Comparison of summer (July to September) lake surface water temperature (LSWT) trends from the shallowest and deepest regions of each lake included in this study (defined as the shallowest and deepest 10% of lake depths; see section 2). Black line shows the 1:1 relationship. (b) Relationship between depth ($\log_{10}$) and summer LSWT warming for each 0.05° pixel that experienced a warming trend across all lakes in this study. The colors illustrate qualitatively the density of observations, where red and blue signifying respectively the greatest and least density of observations.

a strong depth influence on stratification onset. So monomictic lakes may display spatial contrasts in summer LSWT variability to a lesser degree than dimictic lakes. Polymictic lakes are those that mix frequently, which may disrupt and suppress the influence of the factors discussed in this study. This is an area for further study.

In addition to depth, other lake-specific factors are also likely to influence spatial heterogeneity in LSWT trends. For example, in a study of LSWT trends in the Laurentian Great Lakes, Mason et al. (2016) suggested that consistent patterns of upwelling of cooler water along the western coasts of the Great Lakes, as a result of prevailing winds from southwest to northeast, might contribute to slower rates of warming. Specifically, frequent upwelling of hypolimnetic waters may result in cooler warming rates in the shallowest nearshore regions, as bottom waters typically have lower rates of warming compared to surface waters (Kraemer et al., 2015; Livingstone, 2003; Palmer et al., 2014; Richardson et al., 2017; Winslow et al., 2015, 2017), a feature which has also been shown by some modeling studies (Elo et al., 1998; Hondzo & Stefan, 1993; Perroud & Goyette, 2010; Robertson & Ragotzkie, 1990). Climate change could influence wind speed and direction over lakes (Desai et al., 2009), which, in turn, will not only influence stratification patterns (Woolway, Meinson, et al., 2017) but could also influence the frequency of upwelling events and thus spatially resolved LSWT trends. Moreover, a spatial variation in LSWT trends may be influenced by inflows at the lake surface, which can exacerbate the effects of climatic warming in some lakes (Valerio et al., 2015) but contribute to lower warming rates in others (Zhang et al., 2014), in particular the shallow nearshore regions.

While a number of factors can potentially influence intralake summer LSWT variability and trends, we have nonetheless demonstrated that depth covaries with key elements that elucidate systematic differences within large lakes across the Northern Hemisphere. Therefore, our study verifies and expands the results of previous studies on the Laurentian Great Lakes (Mason et al., 2016; Petchprayoon, 2015; Zhong et al., 2016) to a much larger scale, including investigating intralake warming differences in European lakes and also in lakes that are much shallower than those investigated previously. Our analysis could extend beyond 19 study lakes, had we been able to source more bathymetric data at adequate spatial resolution. More extensive analysis will need consistent, comprehensive and accessible depth information for lakes worldwide (Messager et al., 2016).

There are numerous likely implications of our results for lake ecosystems. For example, many ecological processes in lakes, such as fish physiology (Cline et al., 2013), growth potential (Kao et al., 2015), and community structure (Magnuson et al., 1997), are temperature dependent. The observed spatial variation in LSWT trends suggests that the effects of warming on species ranges and ecological dynamics are likely to vary spatially as well, and thermally suitable habitats for both native and invasive species in lakes may change in the future (Magnuson et al., 1990; Mandrak, 1989; Smith et al., 2012), with different regions in lakes experiencing more severe temperature range expansion and contraction. This is of particular importance for the survival of cold-water fishes that require a cold, oxygenated refuge (Jacobson et al., 2010), for example. Knowledge of intralake differences in LSWT trends, as provided by satellite measurements, will help lake managers to identify intralake regions that are most susceptible to change and help identify regions where thermal refuge habitats need protecting.

5. Conclusions

In this contribution, we provide a multilake analysis of the spatial variations in LSWT trends and illustrate the intralake differences in summer LSWT warming. Such variations would not be evident from single-point LSWT time series, whether measured in situ or derived from satellites. Single-point time series have previously been used to examine the causes and wide-ranging ecological consequences of climate change in lakes (Hampton et al., 2008; Kraemer et al., 2017), and in situ measurements continue to be essential to evaluate temperature changes, including those associated with climate change. Nonetheless, significant intralake warming differences suggest that effects from sampling location (Sharma et al., 2015) that must to some degree confound the quantitative understanding and causal attribution of summer LSWT warming at a global scale based mainly on analysis of single-point time series. The strategy that has been adopted for satellite-based time series of using a central location to represent lake temperatures (O'Reilly et al., 2015; Schneider & Hook, 2010) inevitably leads to a partial account of the LSWT response to climate change, at least for the world's largest lakes such as those we have analyzed here. Lake center observations of LSWT tend to overestimate the overall warming rates in these lakes, since central locations are often, although not always, relatively deep. When comparing and assessing interannual variability and warming trends across large lakes, spatially resolved temperature analyses give a more representative picture of LSWT change.

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